DECLARATION OF PRIOR INVENTION UNDER 37 C.F.R. §1.131(a)	Docket No. F0017/7000

Applicant:	Jiankang Huang and Robert C. O'Handley
Serial No:	10/730,355
Filed:	December 8, 2003
For:	HIGH SENSITIVITY, PASSIVE MAGNETIC FIELD SENSOR AND METHOD OF MANUFACTURE
Examiner:	C. A. Renner
Art Unit:	2652

Assistant Commissioner for Patents
Washington, D.C. 20231

The undersigned hereby declares and states:

1. I am the named inventor in the above-identified United States patent application.

2. I am the co-founder and President of Ferro Solutions, Inc., the assignee of the above-identified U.S. Patent Application, and have been employed thereby since its incorporation in April of 2002.

3. I received a BS and MS in physics from the Beijing University in 1985 and 1991, respectively.

4. I was a visiting scientist in the Department of Material Science and Engineering at the Massachusetts Institute of Technology from 1995 to 1998.

5. I have more than ten years research and development experience in ferromagnetic materials, ferroelectric materials and related devices.

6. Prior to October 18, 2002, the effective priority date of US Patent 7,023,206, Viehland, et al., I conceived of the subject matter claimed in the above-identified patent application in conjunction with named co-inventor Robert C. O'Handley.

7. Thereafter, the inventive concepts were memorialized in a pair of written documents, a first entitled "A Novel Vibration Energy Scavenging System", a copy of which is attached hereto as Exhibit A with selected date information redacted, and a second entitled " A Passive Relaxor Piezoelectric Magnetic Sensor", a copy of which is attached hereto as Exhibit B, also with selected date information redacted. Exhibits A and B, both of which are incorporated herein by reference, were submitted to the Office of Naval Research of the United States Navy, as part of Small Business Innovation Research (SBIR) programs.

8. The description and illustrations in Exhibit A, particularly with reference to Figure 2 on page 5 thereof and Figure 6 on page 8 thereof, selected of which have been highlighted for easier identification, establish the inventive concept of a magnetic field sensor having 1) a layer of magnetostrictive material with a magnetization vector that responds to an applied magnetic field by rotating in a plane and generating a stress; 2) a layer of electroactive material, bonded to the layer of magnetostrictive material, that responds to the stress by generating a voltage; and 3) electrodes that measure the voltage generated by the electroactive material in a direction substantially parallel to the plane in which the magnetization vector rotates, as well as electrodes across which appears the voltage generated by the electroactive material in a direction substantially parallel to the direction in which the principal magnetostrictive stress is generated.

9. The description and illustrations in Exhibit B, particularly with reference to Figure 1 on page 4 thereof and sections 3.3 on page 5-7 thereof, establish the sensitivity theories and materials used with the inventive concept.

10. Thereafter, the Office of Naval Research awarded support for further development and research of the concepts described in each Exhibits A and B. A copy of the award notification for subject matter set forth in Exhibit A is attached hereto as Exhibit C with selected date information redacted; Exhibit C being incorporated herein by reference.

11. Subsequently, further refinements and developments to the inventive concepts were conducted in accordance with the SBIR along with the preparation of US Provisional Patent Application Serial No. 60/431,487, filed December 9, 2002, in which the inventive subject matter is also described.

12. The above-identified patent application was filed on December 8, 2003, within 12 months from the initial filing of US Provisional Serial No. 60/431,487 and claims priority thereto.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Huang Jiankang

Jiankang Huang

12/15/2006
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Project Summary: (Appendix B)

A Novel Vibration Energy Scavenging (VES) System

Ferro Solutions proposes to develop a novel Vibration Energy Scavenging System (VES) for naval applications. The technology behind the proposed VES takes advantages of our novel high-sensitivity, passive magnetic electroactive sensors (PME).

. This vibration energy scavenging system will have the advantages of high-output voltage; efficiently work to varying vibration condition and easy implementation for a variety of output requirement.

There has been much demand in recent years for energy scavenging systems for wireless sensor networks. These wireless sensor networks include detection of cracks, corrosion, and impact damage to buildings, bridges, underground structures, ships, submarines, aircrafts and engines. It is imperative that the energy source last the lifetime of the sensors they power.

The development and engineering of relaxor piezoelectric single crystals and magnetostrictive materials make it possible to provide low-cost, and high-sensitivity, passive magnetic electroactive sensors (PME). The sensor is the core of the vibration energy scavenging system.

In phase I, we will demonstrate the feasibility of the vibration energy scavenging system based on the technology of high-sensitivity PME sensor.

In phase II, we will optimize the device designs, further improve materials properties and optimize fabrication process.

COMMERCIALIZATION POTENTIAL

There are numerous commercial and military applications for vibration energy scavenging system. A high-output- voltage, optimizing to varying vibration VES system will have a large market potential.

3. Identification & Significance of the Opportunity

3.1 Background

There has been much demand in recent years for energy scavenging systems for wireless sensor networks. These wireless sensor networks include detection of cracks, corrosion, and impact damage to buildings, bridges, underground structures, ships, submarines, aircrafts and engines. It is imperative that the energy source last the lifetime of the sensors. A sustainable source of energy rather than improved energy storage technologies (e.g. batteries) has to be developed.

Many efforts to realize the energy scavenging system have been made by converting ambient energy sources to electrical energy[1-10]. The sources of energy available will depend on the application. Some possible energy sources are: Solar power, thermal gradients, fluid flow, electromagnetic field, mechanical energy including movement and vibration. Of these sources, solar power and thermal energy are the most familiar and have already been exploited. However, there are many applications where there is insufficient light or thermal energy, e.g. embedded sensors. Vibration Energy Scavenging (VES) System is ideal for sensors on vehicles like ships, submarine and aircraft and engines. A VES system basically consists of two subsystems: an mechanical system (an oscillating mass) to response to ambient vibration and an mechanical-electrical converting system to generate voltage output. There are three basic ways of converting vibration energy to electrical energy: capacitive, inductive and piezoelectric. Capacitive coupling requires a separate voltage source. In inductive converter, the oscillating mass and mechanical-electrical converting system are separated, a design matching ambient vibration is easy to be implemented. But the inductive conversion requires a strong magnetic field and the voltage output is very low. Another disadvantage of the inductive converter is its vibration frequency dependence, the inductive effect is proportional to the relative moving speed between the inductive coil and magnetic field. A typical inductive vibration energy generator[2] is depicted in Figure 1. Piezoelectric and inductive couplings do not require a separate voltage source. In a piezoelectric converter, the oscillating mass has to be integrated with the mechanical-electrical converting system (piezoelectric material) to generate an output voltage. Piezoelectric converters have the advantage of high output voltage. But it is difficult to take advantage of ambient vibration because of the low elastic yield stress of piezoelectric materials.

Ferro Solutions has been developing a novel high-sensitivity, passive magnetic electroactive d_{33} mode (PME33) magnetic sensor. This PME33 magnetic sensor converts magnetic field variation to electrical voltage output by combing magnetostrictive and piezoelectric effects together. Based on the PME33 magnetic sensor, a novel vibration energy scavenging (VES) system is proposed. This VES system will have the advantage of large voltage output and less vibration dependence.

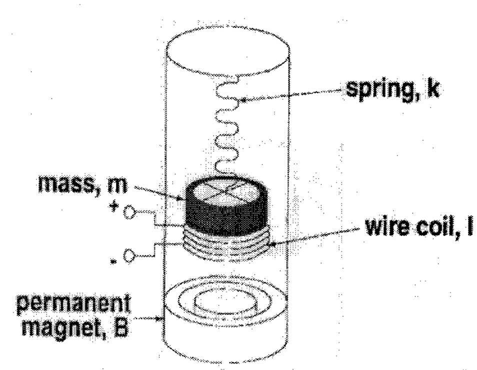

Fig.1 Schematic of inductive converter

3.2 Novel Vibration Energy Scavenging (VES) System

The concept of the high-sensitivity passive magnetic electroactive d_{33} mode (PME33) magnetic sensor and this novel vibration energy scavenging (VES) are depicted in Figure 2 and Figure 3 respectively.

The PME magnetic field sensor is an independent product of FerroSolutions and is briefly described in appendix. It produces an output voltage when exposed to a magnetic field.

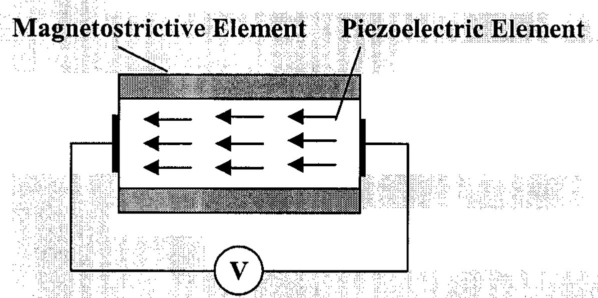

Fig. 2. Side view of the PME33 magnetic sensor

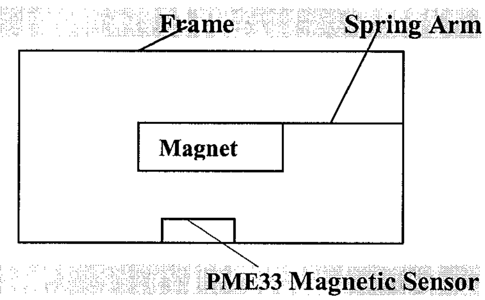

Fig. 3. Side view of the VES System

In the proposed VES system (Fig. 3.), permanent magnet serves as the magnetic field source and oscillating mass. The permanent magnet must move relative to the sensor to harvest energy from the vibration. Either the permanent magnet or the sensor should be coupled to the vibration. The application will dictate which is the best. The arrangement of the magnet and PME33 magnetic sensor is to place the PME magnetic sensor in its most sensitive orientation. As the housing is vibrated, the permanent magnet moves relative to the housing and energy is stored in the magnet-spring system. The PME33 magnetic sensor senses the variation of magnetic field generated by the permanent magnet movement and generate electrical voltage output. There are three major advantages of this design over conventional inductive vibration energy generator. 1) The PME33 magnetic sensor is extremely sensitive to magnetic field variation. A high voltage output is expected. 2) The spring arm can be designed to response a varying vibration directions while the PME33 magnetic sensor is still at its maximum sensitivity. 3) The electrical voltage output of the PME33 magnetic sensor depends only on the magnitude of magnet oscillation. The voltage output of inductive converter depends on both the magnitude and the speed of the magnet oscillation. Theses advantages make this novel VES system work efficiently to varying vibration conditions.

3.4 Operation Principle and Advantages of Proposed VES System

3.4.1 High Voltage Output

Our novel design takes advantage of our high-sensitivity PME33 magnetic sensor. The PME33 magnetic sensor combines higher piezoelectric voltage constant g_{33} of relaxor piezoelectric single crystals and optimized magnetostrictive material.

The voltage V_{33} generated by the PME33 is: $V_{33} = E_{33}L_{33} = g_{33}\sigma_M L_{33}$ (1)

In which E_{33} and L_{33} are the electric field and distance respectively between electrodes. The theoretical limit of the PME33 magnetic sensor can be calculated by using typical value for the parameters in equation (1). For relaxor piezoelectric single crystals, $g_{33} \sim 5.6 \times 10^{-2}$ V/(Nm), $L_{33} \sim 2 \times 10^{-2}$ m, and for the magnetostrictive material, σ_M is $\sim 10^6$N/m^2 per Oe.

The theoretical limit for V_{33} is about 1000 Volts per Oe. Because the magnetostrictive stress may not be fully transmitted to the electroactive element, we expect a quality of order 10 V/Oe.

For our energy converter system, the magnetic filed variation δH generated by the relative motion of the PME33 and a permanent magnet sensing position can be estimated by the following equation:

$\delta H/H_0 \sim 3 \times (\delta Z/Z)$ (2)

In which, H_0 is the magnetic field at the PME33 sensor position when the permanent magnet is at its original position; Z is the distance between the magnet and the PME33 element; δZ is magnitude of magnet oscillation.

For a practical design, r ~ 4mm, H_0 ~ 20 Oe. In the case of strong vibration sources, e.g. milling machine, δr ~ 0.01 to 0.1mm. The theoretical voltage output of this energy converter is about 100 V. For ships and aircrafts with stronger vibration, even higher voltage output is expected.

3.4.2 Efficient VES System to Varying Vibration

The unique magnetic characteristic of our PME33 magnetic sensor allows us to be able to optimize the spring arm design to varying vibration. In this design, the PME33 sensor is particularly sensitive to field changes due to vibrations along two orthogonal axes. The field change is always directed so as to rotate the magnetization in the plane of the magnetic layers and away from it quiescent orientation.

Fig. 4 below schematically represents the two soft magnetic layers (preferably magnetized along their length but annealed so that very little field is required to rotate the magnetization into the horizontal direction). The polling and voltage-measuring direction is the long dimension. If the sensor is placed close to the face of a permanent magnet in either of the two orientations illustrated to the right, the field it senses is sensitive to vibrations along the axes shown by the double-ended arrows. In the orientation shown at right, the device is also sensitive to vibrations along the z direction (provided the device is not centered beneath the magnet) with the field dependence dropping off in a manner similar to that for $H_z(z)$.

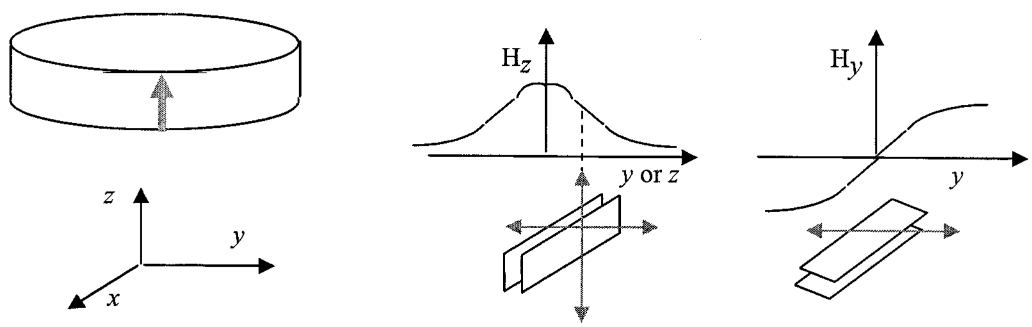

Fig. 4. Left, permanent magnet and coordinate system. Right, dependence of two field components, H_z and H_y, on coordinates of vibration direction indicated by the double-ended arrows.

Our calculations suggest that the inflection point in the $H_z(z)$ occurs at $z = r/2$, where r is the radius of the PM.

One VES system arrangement is depicted in Fig. 5. This design would allow the sensor and PM to vibrate relative to each other as well as independently in two different directions.

The mechanical resonance frequency along each direction could be different so that shocks or vibrations in the two directions could be sensed and harvested efficiently.

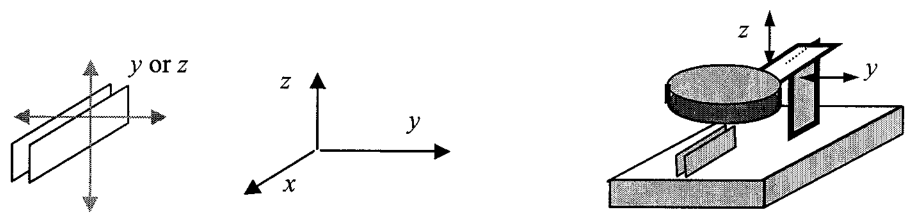

Fig. 5. Left and center, passive magnetic/relaxor sensor oriented to detect variations in H_z. Right, simplified schematic of one arrangement of fixed sensor and suspended permanent magnet. The magnet is suspended on two orthogonal cantilevers that allow it to oscillate relative to the sensor in the z or y directions. The sensor will detect changes in H_z as indicated in Fig. 4.

4. Phase I Technical Objectives

The phase I technical objectives are to design and fabricate a prototype of a vibration energy scavenging system with PME33 magnetic sensor to realize a novel VES system.

5. Phase I - Work Plan

The main task in this Phase I program will be the demonstration of a novel vibration energy scavenging (VES) system. In order to realize this goal, several challenging tasks must be completed. The following subsections detail the technical approach to accomplishing these tasks.

Task #1. g_{33} mode high sensitivity PME magnetic sensor prototype

We will fabricate PME33 magnetic sensor prototype for VES system using optimized magnetostrictive material and commercial grade PZT materials and relaxor piezoelectric single crystals.

Task #2. Magnetic materials selection and optimization

A systemic study will be carried out in optimizing FeCo and amorphous magnetic alloys such as a-FeBSi, a-FeNiMoB. Annealing and shape factor of the magnetic layer sensor/electrode elements will be engineered so they respond with optimal $\lambda(H_0 + \delta H)$ where H_0 is the magnetic field ~ 20 Oe at PME33 sensing position, and δH ~ 1 Oe is the magnetic field variation to be sensed.

Task #3. Permanent magnet and spring arm selection

Geometry, weight and magnetic property of the permanent magnet will be investigated. The geometry and stiffness of the spring arm will be optimized. The magnet and arm will be integrated to form a mechanical system to efficiently response to the ambient vibration.

Task #4. Voltage regulator circuit

Since the voltage output of the vibration energy converter is a time-varying voltage and the vibration source may not be reliable or periodic, the output voltage must be regulated to a desired value before it can be used to power a load circuit. The voltage regulator circuit will be fabricated.

Task #5. Characterization of the VES system

A vibration-generating instrument will be setup to simulate the ambient vibration. And the energy output instrument will be setup to evaluate the VES system.

Task #6. Final report

A final report will be submitted by Ferro Solutions at the completion of the phase I program.

Time Schedule

The entire Phase I program will be completed in six months. Table 1 details the schedule for each main task described in the above subsection.

Table 1. Project Time Schedule

Tasks	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
1. PME33 prototype for the VES system	x	x	x			
2. Materials selection and optimization	x	x	x	x		
3. Permanent magnet and spring arm selection	x	x	x	x		
4. Voltage regulator circuit			x	x	x	x
5. Characterization of the VES system					x	x
6. Final report						x

5. 1. Phase I Option

During the transition period between Phase I and Phase II, FerroSolutions will further optimize the novel VES system including materials and fabrication process based on our Phase I results. All the issues involved in improvement of the device performance will be extensively analyzed. An improved VES system design, fabrication and characterization will be performed.

Appendix. FerroSolutions PME33 Magnetic Sensor

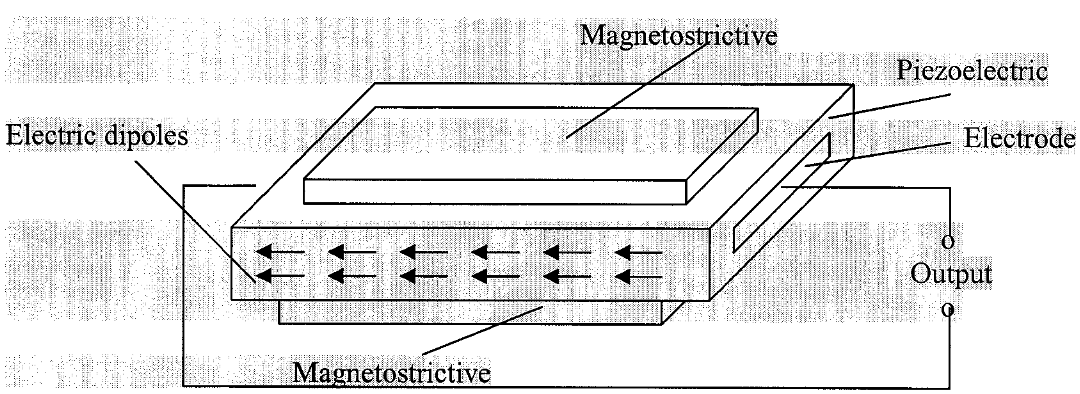

Fig. 6. Schematic of the HPSSM

In PMS magnetic sensor (Fig. 2. and 6), a relaxor piezoelectric component is sandwiched by two magnetostrictive metallic layers. These magnetic metallic layers respond an externally applied magnetic field by exerting a stress on the piezoelectric layer. Voltage output induced in the piezoelectric layer by the magnetostrictive stress is measured via electrodes on both ends of poling direction. The voltage can be very large because 1) this design make use of piezoelectric voltage coefficient g_{33} instead of traditional design which uses g_{31}. For a piezoelectric material, g_{33} can be ~ 5 times larger than g_{31}. 2) The piezoelectric voltage coefficient g_{33} of relaxor piezoelectric single crystal can be ~ 5 times higher than that of normal soft PZT. 3) The distance between the electrodes can be 10 times (Spinix sensor[11]) to 140 times (MRC sensor[12]) larger than that of existing commercial sensors of similar design, which means another 10 to 140 times higher voltage output. So the proposed magnetic sensor can be 100 to 1000 times more sensitive than the existing ones. Calculation shows a theoretic sensitivity of ~ 10^7 nV/nT is expected for the magnetic sensor.

Development of passive solid-state magnetic sensors (PSSM)

Two categories of magnetostrictive/piezoelectric magnetic sensors have been investigated. Magnetostrictive/piezoelectric laminate structure based on the g_{31} mode is the core for both of them. The difference is that one requires an A.C. activation magnetic field provided by a coil. The other is passive without excitation coil.

Several groups in Europe and the United States worked on the active mode sensors[12,14,15]. The GEC-Marconi Research Center (MRC) sensor is a typical active mode sensor (Fig. 5.). In MRC, the magnetostrictive/piezoelectric magnetic sensor consists of a laminate of one piezoelectric layer and one magnetostrictive layer. This element is placed inside a coil through which A.C. excitation and optional D.C. bias current are passed. The sensitivity of 1196 nV/nT was obtained in an element with size of 200 x 25 x 1.44 mm^3.

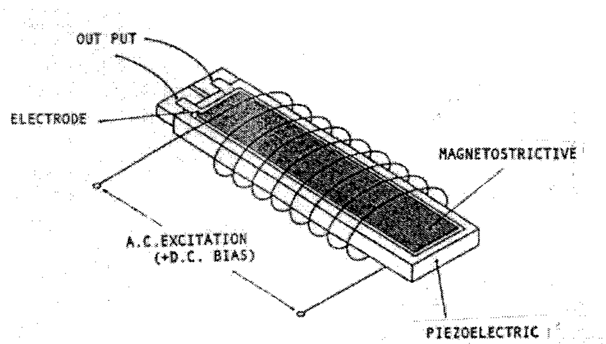

Fig. 5. Schematic of MRC sensor

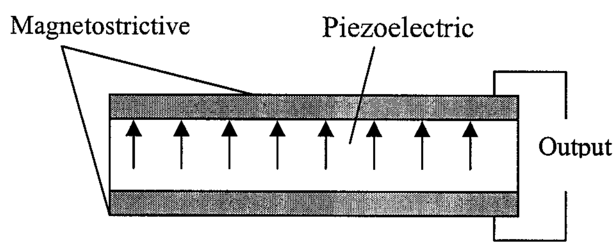

Fig. 6. Schematic of Spinix Sensor

Spinix Corp. developed a series of commercial products based on passive magnetostrictive/piezoelectric laminating structure (Fig.6). With Spinix's design, a robust magnetic sensor with the sensitivity of 28 mV/Oe (280nV/nT) has been realized. Spinix sensors have advantages of low-cost and self-powered. No excitation coil is required for Spinix sensors.

But both of the magnetostrictive/piezoelectric sensors discussed above are based on the g_{31} piezoelectric coupling.

Much higher sensitivity (10^5 nV/nT) is expected by the novel design we proposed combining the extraordinary electromechanical properties of single crystal relaxor piezoelectric and optimizing the materials and fabrication process.

References

1. C. B. Williams and R.B. Yates, "Analysis of a micro-electric generator for Microsystems," in Proc. Transducer'95/Eurosensors *IX*,1995.

2. Rajeevan Amirtharajah and Anantha P. Chandrakasan, "Self-Powered Signal Processing Using Vibration-based Power generation", IEEE Journal of Solid State Circuits, Vol.33,No5, May 1998.
3. D. Friedman, H. Heinreich, and D.-W. Duan, " A low-power CMOS integrated circuit for field-powered radio frequency identification tags," in ISSCC 1997 Dig. Tech. Papers, Feb. 1997, pp.296-297.
4. J. Bouvier, Y. Thorigne, S. Abou Hassan, M. J. Revillet, and P. Senn, "A smart card CMOS circuit with magnetic power and communications interface," in ISSCC 1997 Dig. Tech. Papers, Feb.1997, pp. 296-297.
5. L. A. Geddes, "Historical highlights in cardiac pacing," *IEEE Eng. Med. Biol.,* pp. 12-18, June 1990.
6. T. Starner, "Human powered wearable computing," *IBM Syst. J.,* vol. 35, nos. ¾, pp. 618-629, 1996
7. M. Hayakawa, "Electronic wristwatch with generator," US patent 5001685, Mar. 1991.
8. S. Meninger, et. Al., "Vibration-to-Electric Energy Conversion", *ISPLED*, pp. 48-53.
9. C. Shearwood and R. B. Yates, "Development of an Electromagnetic Microgenerator", *Electronic Letters*, August 1997.
10. H. Glosch, M. Ashauer, U. Pfeiffer, and W. Lang, "A thermoelectric converter for energy supply", *Sensors and Actuators* 74, 1999, pp. 246-250.
11. Yi-Qun Li, and Robert O'Handley, *J. Appl. Sensing technology*, 17, 10(2000).
12. B.J. Lynch and H.R.Gallantree, *GEC Journal of Research*, Vol. 8, No.1, 1990.
13. James E. Lenz, Proceedings of the *IEEE*, 78, 973(1990).
14. M. D. Mermelsten, *IEEE Trans. On Magn.*, Vol. 28, No. 1, January (1992).
15. J. L. Preto, etc. *IEEE Trans. On Magn.*, vol. 34, No.6, November (1998).

6. Related Work

The P.I. has made and characterized a variety of magnetic field sensors including prototype magnetostrictive/PZT passive field sensors.

The CTO of Ferro Solutions has extensive experience with magnetic materials in general and in particular has invented and published extensively on magnetic sensors and devices.

Ferro Solutions will work closely with Prof. Yet-Ming Chiang, consultant for this program, in piezoelectric materials optimization and evaluation.

7. Relationship with Future Research or Research and Development

The goal of this program is to provide the DoD and the commercial market with a novel vibration energy scavenging (VES) system. The anticipated results from the proposed phase I program will provide critical information on optimization and fabrication of the VES system during the phase II effort. Ferro Solutions is committed to the commercialization of successful product concepts which emerge from government sponsored programs. The device design and fabrication knowledge generated over the contract period will be crucial for the commercial device development and manufacturing.

8. Commercialization Strategy

Ferro Solutions is a recent start-up company with the mission of developing and manufacturing novel materials-based device products, specifically ferromagnetic and ferroelectric's materials based devices.

A very large market is anticipated for the novel VES system. It is expected that this VES system will be integrated into many military and commercial applications.

Our strategy to commercialize this technology is to develop and demonstrate our unique technology and then team up with the users of the VES, e.g. wireless sensor network manufacturers and users who are technology capable and have large volume manufacture and marketing capability.

9. Key Personnel

Mr. Jiankang Huang, Principal investigator
President, Ferro Solutions

Mr. Huang has more than ten years R&D experience in ferromagnetic materials, ferroelectric materials and related devices. He is the president of Ferro Solutions and a research affiliate at MIT. He has been in charge of magnetostrictive materials development in high-sensitivity magnetic sensors at NZAT Applied Technologies from 1998 to 2000. He successfully developed magnetostrictive thin films for two Phase II SBIR projects. After NZAT was acquired by Corning Corp. in 2000, he has been working in electro-optical ceramic materials and devices. Mr. Huang was a visiting scientist in Department of Material Science and Engineering at MIT from 1995 to 1998, where he and his colleagues discovered the magnetic-field-induced strain in the martensitic phase of single-crystal shape memory material Ni_2MnGa. This discovery leads to a new class of actuator materials: Ferromagnetic Shape memory Alloy (FSMA). Before coming to MIT, Mr. Huang worked in magnetic materials in Chinese Academy of Sciences in Beijing, China. He received his BS and MS in physics at Beijing University in 1985 and 1991 respectively.

Selected Publications:

- **Patent (pending)**
  "Dual-Tuning Microwave Devices Using Ferroelectric/Ferrite Layers", Hua Jiang, Wei Hu, Vladimir Fuflyigin, Shaohua Liang, Yi-Qun Li, and **Jiankang Huang.**
- **Journal Papers**
  1. "Field-induced strain under load in Ni-Mn-Ga magnetic shape memory materials", S.J.Murray, M. Farinelli, C. Kantner, **J.K.Huang**, S.M.Allen, and R.C.O'Handley, J.Appl Phys.,83, 7297(1998).
  2. "Metalorganic Chemical Vapor Deposition of Magneto-Optical Ce:YIG Thin Films", Yi-Qun Li, Mondher Cherif, **Jiankang Huang**, Wayne Liu, and Qiushui Chen, Proceedings of the 1998 MRS Spring Symposium, 517, 449(1998).
  3. "Magnetic-field-induced strains in Ni_2MnGa shape-memory alloy", K.Ullakko, **J.K.Huang**, C.Kantner, V.V.Kokorin and R.C.O'Handley, J. Appl. Phys. 81, 5416(1997).
  4. "Magnetically controlled shape memory effect in Ni_2MnGa intermetallics", K. Ullakko, **Jiankang Huang**, V. V. Kokorin, and R. C. O'Handley, Scripta Materialia, 36 1133,(1997).
  5. "Large magnetic-field-induced strains in Ni_2MnGa single crystals", K. Ullakko, **J. K. Huang**, C. Kantner, and R. C. O'Handley, and V. V. Kokorin, Appl. Phys. Lett. 69, 1966(1996).

Dr. Robert O'Handley, Senior Scientist
Chief Technology Officer, Ferro Solutions

R.C. O'Handley received his Ph.D. in Physics in 1972 from the Polytechnic Institute of Brooklyn (now the Polytechnic University) for magnetic resonance studies of gadolinium thin films. He was a National Research Council Postdoctoral Research Associate at Michelson Lab, China Lake, CA, where he used polarization modulated ellipsometry to study surfaces of silver films in ultrahigh vacuum.

In July, 1974 he joined Allied Chemical's Materials Research Center, Morristown, NJ, to start a group investigating the magnetic properties of amorphous metallic alloys. At Allied he contributed to the

understanding of both the fundamental and technical properties of these novel materials. Particularly noteworthy are his pioneering studies of magnetoelastic phenomena and his successful development of high-induction metallic glasses for power transformer applications.

In Sept. 1978 he became a research staff member at IBM's Watson Research Center where he solved materials problems facing the development of multilayer composite chip carriers. Since coming to MIT in January 1981 he has expanded his research horizons to include synthesis and characterization of strongly magnetic icosahedral phases as well as pioneering processing and characterization of new high-energy-product Fe-Nd-B permanent magnets. He also contributes to the development of high T_C oxide superconductors and perpendicular magnetization via magnetoelastic coupling in epitaxial Cu/Ni/Si (001) films. Most recently, he has discovered and pursued the development of giant magnetic-field-induced strains in martensitic Heusler alloys based on the shape-memory material, Ni_2MnGa.

Dr. O'Handley has authored a widely used textbook, *Modern Magnetic Materials, Principles and Applications*, written several chapters for other books and published more than 200 scientific and technical papers on magnetic, electrical and other physical properties of solids. He is active in the IEEE Magnetics Society and in the annual Conference on Magnetism and Magnetic Materials, for which he has been a publications chairman, secretary and treasurer. He is a member of the scientific advisory board of the Chinese National Magnet Lab, Beijing, PRC, and is on the editorial board of Materials Letters.

He holds sixteen U.S. and international patents on magnetic materials and devices. His discoveries made possible the development of a new active materials company, AdaptaMat, as well as sensor manufacturers, Spinix and FerroSolutions (where he is the Chief Technology Officer). He has consulted for many industries including IBM, DEC/Quantum Corp., and Sensormatic.

Selected Publications

Relevant Books, Chapters and Review Papers

1. "*Modern Magnetic Materials: Principles and Applications*", R. C. O'Handley,(Wiley,1999).
2. "Hall Effect in Amorphous Metals", chapter in *The Hall Effect and Its Applications*, T.R. McGuire, R.J. Gambino and R.C. O'Handley, ed. C.-L.Chien and C.R. Westgate (Plenum, NY, 1980), p.137.
3. "Hall Effect Formulae and Units", R.C. O'Handley, chapter in *Hall Effect and Its Applications,* ed. C.-L. Chien and C.R. Westgate (Plenum Press, NY, 1980) p. 417.
4. "Fundamental Magnetic Properties", R.C. O'Handley, chapter in *Amorphous Metallic Alloys*, ed. F.E. Luborsky (Butterworths, London, 1983) p. 257.
5. "Physics of Ferromagnetic Amorphous Alloys", R.C. O'Handley, Invited review paper, J. Appl. Phys. **62**, R15 (1987).
6. "Magnetostriction and Magnetoelastic Effects", R.C.O'Handley, Chapter in *Modern Methods in Materials*, (John Wiley, N.Y., 1999).
7. "Magnetic Materials", R. C. O'Handley, entry in *Encyclopedia of Physical Science and Technology*, Third Edition, ed. R.A. Myers (Academic Press, 2001).

Other Sensor-related Publications

1. "An Innovative Passive Solid-State magnetic Sensor", Yi-Qun Li, and Robert O'Handley, J. Appl. Sensing technology, 17, 10(2000).
2. "Magnetostriction of Ferromagnetic Metallic Glasses", R.C. O'Handley, Sol. St. Comm. **21**, 1119 (1977).
3. "Temperature Dependence of Magnetostriction in $Fe_{80}B_{20}$ Glass", R.C. O'Handley, Sol. St. Comm. **22**, 485 (1977).

4. "Spontaneous Hall Effect and Resistivity of Fe-Co-Ni-B Glasses", R.C. O'Handley, Phys. Rev. **B 18**, 2577 (1978).
5. "Magnetostriction of $Fe_{100-x}B_x$ Glasses", R.C. O'Handley, M.C. Narasimhan and M.O. Sullivan, J. Appl. Phys. **50**, 1633 (1979).
6. "Elastic Constant Anomaly in $Fe_{80-x}Mo_xB_{20}$ Metallic Glasses",C.-P. Chou and R.C. O'Handley, J. Non-cryst. Sol. **40**, 417 (1980), and in *Electrical, Magnetic and Optical Properties of Glasses*", ed. M. Tomozawa et al., (North Holland, NY, 1980) p. 417.
7. "Magnetostriction in $Co_{80-x}T_xB_{20}$ (T = Fe, Mn, Cr, V) Glasses", R.C. O'Handley and M.O. Sullivan, J. Appl. Phys. **52**, 705 (1981).
8. "Opportunities in Magnetic Anisotropy and Magnetostriction", R.C. O'Handley, Mat Sci. and Eng. **B 3**, 365 (1989).
9. "Magnetic Materials for EAS Sensors", R.C. O'Handley, J. Mtls. Engineering and Performance **2**, 211 (1993).
10. "Analysis of a Magnetoelastic Sensor", R.L. Copeland, M. Kopp, and R.C. O'Handley, IEEE Trans. Magnetics **MAG-30**, 3399 (1994).
11. "New Spin Valve magnetic field sensor combined with strain sensing and strain compensation", R.C. O'Handley and J.R. Childress, IEEE Trans. **MAG-31**, 2450(1995).
12. "Development of a Pinned Wall Sensor Using Cobalt-rich, Near-zero Magnetostrictive Amorphous Alloys", C.K. Kim and R.C. O'Handley, Metal. and Mater. Trans. **28A**, 423 (1997).
13. "6% magnetic-field-induced strain by twin-boundary motion in ferromagnetic Ni-Mn-Ga", S.J. Murray, M. Marioni, S.M. Allen, R.C. O'Handley and T.A. Lograsso, Appl. Phys. Lett. **87**, 886 (2000).
14. "AC performance and modeling of ferromagnetic shape memory actuators", Christopher P. Henry, Jorge Feuchtwanger, David Bono, Miguel Marioni, Pablo G. Tello, Marc Richard, Samuel M. Allen, and Robert C. O'Handley, Proc. SPIE **4333.**, **151** (2001).

10. Facilities/Equipment

Ferro Solutions has full access to Dr. Robert O'Handley's Lab at MIT for research and development. Manufacturing facilities will be built up in Ferro Solutions to produce commercial products.

The major facilities and equipments in Dr. Robert O'Handley's Lab include the followings:

Vibrating Sample Magnetometers (VSM), torque magnetometer, inductance and impedance bridges, spectrum analysis and other electronic for low-field magnetic and magnetostrictive measurement.

A broad range of processing and characterization equipment, relevant to development of piezoelectric materials, is available in Prof. Yet-Ming Chiang's Lab, including the following. 1) A laboratory for inorganic materials synthesis including wet chemical equipment, glove boxes, freeze-driers, calcining and sintering furnaces, hot-pressing facilities. 2) Dielectric, electrical, electromechanical, and thermomechanical testing facilities. 3) Materials characterization facilities including environmental SEM, high resolution SEM, TEM, STEM, AFM, and surface analytical equipment.

11. Consultants

1. Yet-Ming Chiang, Kyocera Professor of Ceramics, MIT.

Project Responsibilities: optimize and evaluate piezoelectric materials.

Professional Employment, Other Positions Held, and Affiliations:

Professor, Department of Materials Science and Engineering, MIT, July 1994 - present
Visiting Research Scientist, DuPont Central Research, Wilmington, Delaware, Jan.-Dec. 1992
Associate Professor, MIT, July 1988 - June 1994
Assistant Professor, MIT, January 1985 - June 1988

Editorial Boards of *Current Opinion in Materials Science and Engineering, Journal of the American Ceramic Society, Journal of Electroceramics*
Materials Consultant, *The Oklahoma City National Memorial Foundation*, April 1998-August 1999

Honors:
Ross Coffin Purdy Award, (with H.D. Ackler, for best paper in the *Journal of the American Ceramic Society* in 1999), The American Ceramic Society, April 2001
R.M. Fulrath Award, The American Ceramic Society, 2000
F.H. Norton Award (Outstanding New England Ceramist), The American Ceramic Society, 1999
Fellow, The American Ceramic Society, 1998
Kyocera Professorship, 1989-present
ONR Young Investigator Award, 1988-1991
Mitsui Career Development Award, 1987-1989
DuPont Faculty Development Award, 1985-1987
IBM Graduate Fellowship, 1982-1984

Selected Relevant Publications
- S.A. Sheets, A.N. Soukhojak, N. Ohashi and Y.-M. Chiang, "Relaxor Single Crystals in the $(Bi_{1/2}Na_{1/2})_{1-x}Ba_xZr_yTi_{1-y}O_3$ (BNBZT) System Exhibiting High Electrostrictive Strain," *J. Appl. Phys.*, **90**[10] 5287-5295 (2001).
- B.P. Nunes, J. Shen, A.N. Soukhojak and Y.-M. Chiang, "Shaped Growth of Oriented Single Crystal Rods and Fibersin the $(Bi_{1/2}Na_{1/2})_{1-x}Ba_xZr_yTi_{1-y}O_3$ (BNBZT) System," Proceedings of 10th US-Japan Seminar on Dielectric & Piezoelectric Ceramics, Newport, RI, Sept. 27-29, 2001.
- N. Ohashi, A. N. Soukhojak, G. W. Farrey, S. A. Sheets, and Y.-M. Chiang, "Liquid Phase Epitaxial Growth of Perovskite $(Bi,Na)TiO_3$ and Solid Solutions on $SrTiO_3$ (001) Substrates," *Proceedings of the 2000 12th IEEE International Symposium on Applications of Ferroelectrics*, IEEE Catalog Number 00CH37076 (ISBN 0-7803-5940-2), pp. 553-556 (2001).
- A.N. Soukhojak and Y.-M. Chiang, "Generalized Rheology of Active Materials," *J. Appl. Phys.*, **88**[11] 6902-6909 (2000).
- A.N. Soukhojak, H. Wang, G.W. Farrey, and Y.-M. Chiang, "Superlattice in Single Crystal Barium-Doped Sodium Bismuth Titanate," J. Phys. Chem. Solids, 61[2] 301-304 (2000).
- Y.-M. Chiang, G.W. Farrey, and A.N. Soukhojak, "Lead-Free High Strain Single Crystal Piezoelectrics," Appl. Phys. Lett., 73[25] 3683-3685 (1998).

Education
Sc.D. M. I. T., 1985.
S.B. M. I. T., 1980.

2. David Bono, Electronic Engineer, Research Affiliate of MIT
Project Responsibilities: Electronic setup for vibration simulation and VES system evaluation.

2000 – 2001: Consultant to ADE Technologies and Research Affiliate, MIT-DMSE, Magnetic Materials Group

1997 - 2000: ADE Technologies, Newton MA, VP of R&D, Digital Measurement Systems Div.

1984 – 1997: Digital Measurement Systems Inc., Burlington, Massachusetts, VP, Founder, Principal designer of many products including: vibrating sample magnetometers, torque magnetometers, Kerr-effect magnetometers, Hall-effect gaussmeters, computer hard disk

magnetic characterization systems with fully automatic robot loading/unloading of disks in a clean room for production quality control. Design of these products included software (using Pascal, HP Basic, Microsoft C++, Microsoft Visual Basic, LabView), mechanical, analog electronics, and digital electronics design. This equipment required the design of state-of-art ultra-low-noise bipolar electromagnet power supplies at 2-15 kW power levels, low noise preamplifiers for magnetic recording signal detection, and wide dynamic range data acquisition systems. DMS installed about 250 ($125,000 to $250,000) systems worldwide during this period. David has made over 40 trips to Japan, 10 to South Korea, 5 to India as well as about 100 installations in the USA and Europe.

In February of 1997, DMS merged with ADE in a stock for stock deal.

1982 – 1984: Varian, Lexington, Massachusetts, Micro-Bit Division. Responsible for electron beam lithography analog system design.

1978 – 1982: Control Data, Lexington, Massachusetts, Micro-Bit Division. Responsible for electron beam memory and then electron beam lithography analog system design including: 10,000 Volt, 1 ppm stability, power supplies, 1000 V bipolar electrostatic deflection amplifiers that settled to .01% in 30 us, 16 bit digital-to-analog converters for the deflection systems, and assembly language programmed test equipment for those systems.

1976 – 1978: Micro-Bit Corporation, Lexington, Massachusetts, Analog electrical engineer building test circuits and designing new circuits for control of the electron beam memory.

1975: Advent Corporation, Cambridge, Massachusetts. Constructed process equipment to support construction of the Video Beam Projection Television product. This included a "spot knocker" which generated 200,000 VAC on top of 300,000 VDC to vaporize contaminants inside color projection cathode ray tubes.

1974: dbx Corporation, Newton, Massachusetts, Constructed ultra-low-distortion sine wave oscillators, distortion measuring filters, and log-anti-log amplifiers for professional audio signal processing applications. Also developed a low distortion audio power amplifier for internal company use.

David is an expert in analog instrumentation, bipolar linear power supply design, linear motor control, precision temperature control, low noise FET amplifiers. He also has extensive experience in mechanical design and in using AutoCAD software. When at DMS he set up a complete machine shop for R&D use and operated and maintained all the tools. He has a MagNet software license which permits him to make detailed magnetic field simulations. He also designs his own circuit boards using Cadence OrCAD Division, Schematic Capture, PC Layout, and PSpice CAD tools.

12. Prior, Current or Pending Support of Similar proposals or Awards.

No prior, current or pending support for the proposed work.

13. Cost Proposal

PROPRIETARY
U.S. DEPARTMENT OF DEFENCE
SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM
COST PROPOSAL

1. Name of offeror: Ferro Solutions
2. Home office address: 204 Norfolk Street, Cambridge, MA 02139
3. Location where work will be performed: 77 Mass Ave. Cambridge, MA 02139
4. Title of proposed effort: A Novel Vibration Energy Scavenging System
5. Taxpayer ID #*:
5. CAGE Code*:
6. Topic number and title: N02-064
7. Total dollar amount of proposal: **$ 99,985** **Base** **69,991** **Option** **29,994**

			Proposal		Option	
8. Direct Materials Costs						
Type	Unit Cost	Unit	Qty	$	Qty	$
PZT-5 compressional crystals	650.00	lot	1	650		
FeCo Alloy						
Ni Alloy						
Metal Glass						
	Total Material Costs			650		0
9. Materials Overhead	None					
10. Direct Labor						
Type		Hourly Rate	Hours	$	Hours	$
Principal Investigator	HUANG, Jiankang		470	18,800	240	9,600
Senior Scientist (magnetic)	O'HANDLEY, Robert		80	4,000	40	2,000
11. Total Direct Labor & Overhead			550	38,760	280	18,360
12. Equipment Usage						
Type		Rate/hr	Hours	$	Hours	$
Lab usage		10	310	3,100	114	1,140
	Total Equipment Usage Cost			3,100		
13. Special Equipment				0		
14. Travel (conference)				0		
15. Subcontracts				0		
15 A. Piezoelectric materials	**Chiang, Yet-Ming**			5,000		
15 B. Electronic Circuits	**Bono, David**			7,000		2,500
16. Other direct costs						
	Sub – Total (7 - 15)			54,510		23,360
17. G&A Expense	All Cost above this line			10,902		4,672
18. Royalties			0.0%	0		0
19. Fee or Profit	All Cost above this line		7.0%	4,579		1,962
20. Total Cost and Fee or profit				69,991		29,994

21. Signed by ____________ [redacted] Name and Title: Jiankang Huang President

22.a Has any executive agency of the United States Government performed any review of your accounts or records in connection with any other government prime contract or subcontract within the past twelve months? No

b. Will you require the use of any government property in the performance of this proposal? No

c. Do you require government contract financing to perform this proposed contract? Yes, Prograss Payments

23. Type of contract proposed: Fixed price

* FerroSolutions is not yet incorporated at this moment. Taxpayer ID and CAGE Code will be available before award.

Project Summary: (Appendix B)

A Passive Relaxor Piezoelectric Magnetic Sensor

Ferro Solutions proposes to develop a novel high-sensitivity passive relaxor piezoelectric magnetic sensor for naval applications. The technology behind the proposed magnetic sensor takes advantages of the extraordinary electromechanical properties of relaxor piezoelectric single crystals. This sensor will have the advantages of low-cost, low-power-consumption and high-sensitivity.

There are a large number of applications, both military and commercial, which need low-cost, low-power-consuming and high sensitivity magnetic sensors, including i) magnetic detection and classification of ships, sea mines and unexploded ordnance for Navy, ii) security for installations, perimeters, and borders, and iii) monitoring of the battlefield, urban or highway traffic.

The development and engineering of relaxor piezoelectric single crystals and magnetostrictive materials make it possible to provide low-cost, low-power-consumption and high-sensitivity magnetic sensors.

In phase I, we will demonstrate the feasibility of this high-sensitivity, low-cost and low-power-consumption magnetic sensor with an engineering sensitivity projected at 10^5 nV/nT at 0.1 nT. The theoretical limit for the sensitivity of the proposed device is 10^7 nV/nT.

In phase II, we will optimize the device designs, further improve materials properties and optimize fabrication process.

COMMERCIALIZATION POTENTIAL

There are numerous commercial and military applications for high-sensitivity magnetic sensors. A high-sensitivity sensor with a low-cost will have a large market potential. Further, the P.I. has experience in fabrication of passive magnetostrictive/piezoelectric solid-state sensors.

3. Identification & Significance of the Opportunity

The objective of this proposal is to demonstrate the feasibility of a high-sensitivity passive relaxor piezoelectric magnetic sensor based on multifunction smart structure technologies and development of the extraordinary electromechanical properties of single crystal relaxor piezoelectric. The concept of this magnetic sensor is depicted in Figure 1 and promises a new generation of low-cost, low-power-consumption and high-sensitivity solid-state magnetic sensors. A relaxor piezoelectric component is sandwiched by two magnetostrictive metallic layers. These magnetic metallic layers respond an externally applied magnetic field by exerting a stress on the piezoelectric layer. Voltage output induced in the piezoelectric layer by the magnetostrictive stress is measured via electrodes on both ends of poling direction. The voltage can be very large because 1) this design make use of piezoelectric voltage coefficient g_{33} instead of traditional design which uses g_{31}. For a piezoelectric material, g_{33} can be ~ 5 times larger than g_{31}. 2) The piezoelectric voltage coefficient g_{33} of relaxor piezoelectric single crystal can be ~ 5 times higher than that of normal soft PZT. 3) The distance between the electrodes can be 10 times (Spinix sensor[1]) to 140 times (MRC sensor[2]) larger than that of existing commercial sensors of similar design, which means another 10 to 140 times higher voltage output. So the proposed magnetic sensor can be 100 to 1000 times more sensitive than the existing ones. Calculation shows a theoretic sensitivity of ~ 10^7 nV/nT is expected for the proposed magnetic sensor. The proposed technology holds the potential for developing low-cost, high-sensitivity (10^{-6} Oe), low-power-consumption magnetic sensors.

Primary applications for the micromagnetic sensor would be for i) magnetic detection and classification of ships, sea mines and unexploded ordnance for Navy, ii) security for installations, perimeters, and borders, and iii) monitoring of battlefield, urban or highway traffic.

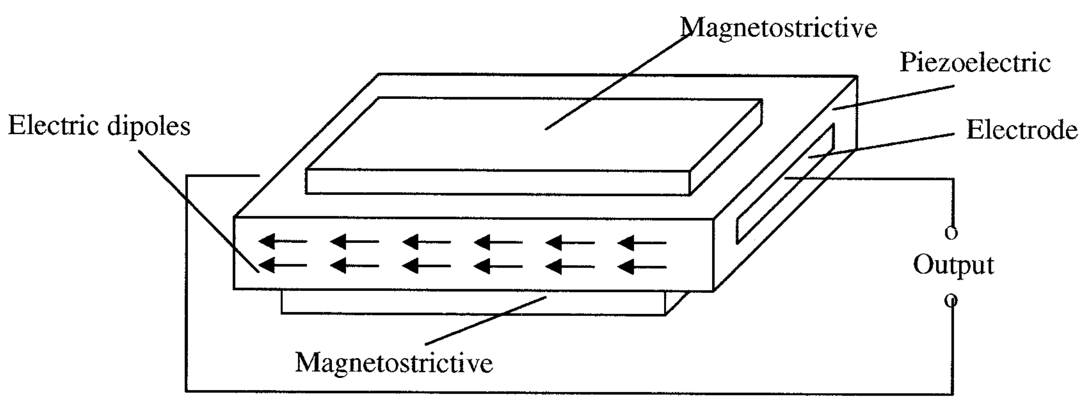

Fig. 1. Schematic of the magnetic sensor

3.1 Background

There is an acute need for development of low-cost, low-energy-consuming magnetic sensors with medium to high sensitivity (10^{-6} Oe) for magnetic anomaly detection (MAD). The commonly used low cost magnetic sensors have only a sensitivity of 10^{-3} Oe, which is not sensitive enough for the purpose of MAD in the battlefield[3]. The existing magnetic sensors are not suitable in terms of cost, sensitivity and energy consumption.

Hall effect field sensors, while very compatible with microelectronics, suffer from a limited sensitivity, and a high level of 1/f noise.

Magnetoresistors generally have a high sensitivity at fields of order of 0.5-200Oe, but are subject to hysteresis due to domain wall effects.

Inductive coils find many applications in proximity and distance sensors, but the miniaturization of coils is difficult.

The fluxgate magnetometer is a highly sensitive magnetic sensor. But the main challenges are the three-dimensional structure of the coils and the low magnetic permeability of integrated ferromagnetic cores.

High-sensitivity magnetic sensors, SQUID gradiometers, optically pumped magnetometers, magneto-optical sensors, and fiber-optical magnetometers are expensive and very difficult to maintain.

Other semiconductor magnetic sensors, magnetodiodes and magnetotransistors basically rely on the Hall effect and suffer similar problems even though their performance is improved.

3.2. Development of magnetostrictive/piezoelectric magnetic sensors

Two categories of magnetostrictive/piezoelectric magnetic sensors have been investigated. Magnetostrictive/piezoelectric laminate structure based on the g_{31} mode is the core for both of them. The difference is that one requires an A.C. activation magnetic field provided by a coil. The other is passive without excitation coil.

Several groups in Europe and the United States worked on the active mode sensors[2,4,5]. The GEC-Marconi Research Center (MRC) sensor is a typical active mode sensor (Fig. 2.). In MRC, the magnetostrictive/piezoelectric magnetic sensor consists of a laminate of one piezoelectric layer and one magnetostrictive layer. This element is placed inside a coil through which A.C. excitation and optional D.C. bias current are passed. The sensitivity of 1196 nV/nT was obtained in an element with size of 200 x 25 x 1.44 mm^3.

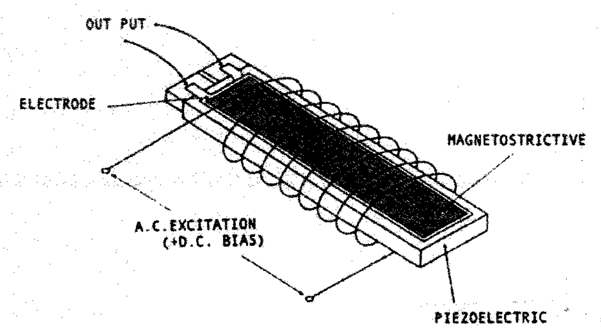

Fig. 2. Schematic of MRC sensor

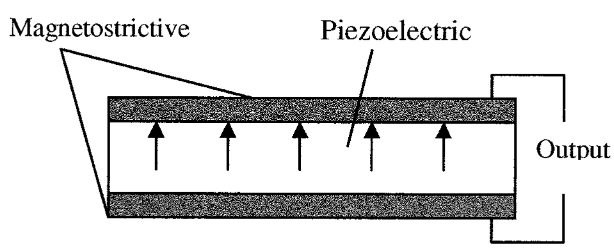

Fig. 3. Schematic of Spinix Sensor

Spinix Corp. developed a series of commercial products based on passive magnetostrictive/piezoelectric laminating structure (Fig.3). With Spinix's design, a robust magnetic sensor with the sensitivity of 28 mV/Oe (280nV/nT) has been realized. Spinix sensors have advantages of low-cost and self-powered. No excitation coil is required for Spinix sensors.

But both of the magnetostrictive/piezoelectric sensors discussed above are based on the g_{31} piezoelectric coupling.

Much higher sensitivity (10^5 nV/nT) is expected by the novel design we proposed combining the extraordinary electromechanical properties of single crystal relaxor piezoelectric and optimizing the materials and fabrication process.

3.3 The Proposed Magnetic Sensor Operation Principle and Advantages

Our novel design combines the higher piezoelectric voltage constant g_{33} of relaxor piezoelectric single crystals. This makes it possible to build a low-cost, low-power-consumption, and robust magnetic sensors with much higher sensitivity.

At frequencies far below resonance, the voltage coefficients g_{ij} are related to the charge coefficients d_{ij} by the dielectric constant K^T_i.

The equations is: $$d_{ij} = K^T_i \, \varepsilon_0 \, g_{ij} \quad (1)$$

The voltage V_{ij} generated by the g_{ij} mode is: $V_{ij} = E_{ij} L_{ij} = g_{ij} \sigma_M L_{ij} = d_{ij} \sigma_M L_{ij}/(K^T{}_i \varepsilon_0)$ (2)

In which E_{ij} and L_{ij} are the electric field and distance respectively between electrodes. The current magnetostrictive/piezoelectric magnetic sensors are based on V_{31} sensing. The sensor we proposed is V_{33} model. Since d_{33} is typically 3 to 5 times d_{31}, L_{33} is 10 to 100 times L_{31}, and d_{33} of relaxor piezoelectric single crystals is 3 to 5 times that of conventional PZT, the proposed sensor can be 1000 times more sensitive than the existing ones.

The theoretical limit of the proposed magnetic sensor can be calculated by using typical value for the parameters in equation (2). For relaxor piezoelectric single crystals, $K^T{}_3$ is ~ 5000, d_{33} ~ 2500 pC/N, $\varepsilon_0 = 8.9 \times 10^{-12}$ farads/meter, $L_{33} \sim 2 \times 10^{-2}$ m, and for the magnetostrictive material, σ_M is ~ 10^6N/m^2 per Oe.

The theoretical limit for V_{33} is about 1000 Volts per Oe, ~ 10^7 nV/nT. Because the magnetostrictive stress may not be fully transmitted to the electroactive element, we expect a quality of order 10^5 nV/nT.

3.3 Materials Selection

For the magnetic sensor material, large magnetostriction λ alone is not enough. Two major requirements on the magnetostrictive materials have to be met:

1. A large Young's modulus E is required so that the magnetostrictive response can be transferred to the piezoelectric layer as a large stress.
2. A small anisotropy that allows the material to be saturated in a field of strength governed by the range of fields to be measured.

For measuring very weak fields, a magnetoelastic figure of merit is the ratio

$$Q = E\lambda_s^2/2K_u \sim E\lambda_s^2 H^4/H_a^5$$

Q is maximized when the material gives the most strain in the weakest fields. Amorphous magnetic alloy can be field annealed to be magnetized to saturation in fields of 10^{-3} to 10 Oe. In a material such as a-FeBSi ($\lambda_s = 35 \times 10^{-6}$, $M_s = 1400$ emu/g), $E = 10^{12}$ d/cm^2, $K_u = M_s H_a/2$ can be as small as 10^3 erg/cm^3 (H_a ~ 1-2 Oe), so Q = 1.2. For a highly magnetostrictive material such as Terfenol-D, $E = 5\times10^{11}$ d/cm^2, $\lambda_s = 1750\times10^{-6}$, $M_s = 800$ emu/cm^3, $K_a = 1\text{-}4\times10^5$. Thus, for Terfenol-D, $Q = 0.01$, which is much lower than that for the lower λ_s amorphous material.

Nickel and many iron-nickel alloys are good choices because both anisotropy and magnetostriction can be controlled over reasonably wide ranges. FeCo Permendur is another good choice because of its relatively large λ_s, E and near zero K_u. Amorphous magnetic alloys remain the best choice for low field measurements because extremely small magnetic anisotropy can be achieved.

Most of the piezoelectric materials presently in use as sensor or transducer elements are ceramics of the lead zirconate titanate (PZT) family. Typical piezoelectric coefficients of PZTs are d_{31} = 100pC/N and d_{33} ~ 400 to 600 pC/N. To achieve a high piezoelectric coefficient, "soft" PZT can be made by compositional engineering. But, this enhanced piezoelectricity comes at the expense of poor temperature dependence, less polarization stability and large hysteresis.

Ultrahigh piezoelectric coefficient with low hysterisis has been reported recently for relaxor perovskites such as $Pb(Zn_{1/3}Nb_{2/3})O_3 - PbTiO_3$ (PZN-PT) and $Pb(Mg_{1/3}Nb_{2/3})O_3 - PbTiO_3$ (PMN-PT). Maximum piezoelectric coefficients d_{33} = ~ 2500pC/N has been realized for PZN-8%PT single crystal[6]. Such piezoelectric coupling promises a new category of high sensitivity (10^{-6} Oe) passive solid-state magnetic sensor.

Finally the magnetostrictive and piezoelective components have to be matched so that the magnetic component responds with maximum stress at the field of interest and this stress is of sufficient magnitude to produce a good signal to noise electric output in the piezoelectric layer.

4. Phase I Technical Objectives

The phase I technical objectives are to design and fabricate a prototype of a d_{33} mode PZT sensor and a relaxor single crystal /magnetostrictive structure to realize a passive or self powered magnetic sensor element with a high sensitivity to magnetic fields of order 10^{-6}Oe.

5. Phase I - Work Plan

The main task in this Phase I program will be the demonstration of two new high sensitivity magnetostrictive/piezoelectric magnetic sensors. In order to realize this goal, several challenging tasks must be completed. The following subsections detail the technical approach to accomplishing these tasks.

Task #1. g_{33} mode sensor prototype using commercial grade PZT materials

We will fabricate a g_{33} mode sensor prototype using optimized magnetostrictive material and commercial grade PZT materials.

Task #2. Magnetic materials selection and optimization

A systemic study will be carried out in optimizing FeCo and amorphous magnetic alloys such as a-FeBSi, a-FeNiMoB. Annealing and shape factor of the magnetic layer sensor/electrode elements will be engineered so they respond with optimal $\lambda(H_0 + \delta H)$ where H_0 is the earth's magnetic field ~ 0.5 Oe, and δH ~ 10^{-6} Oe is the magnetic field anomaly to be sensed.

Task #3. Piezoelectric materials optimization

We expect to demonstrate relaxor piezoelectric single crystals with high piezoelectric coupling coefficients. The relaxor piezoelectric single crystals will be optimized so that it has peak polarization for $\sigma = \sigma_M = Y_m(H_0 + \delta H)\ \lambda(H_0 + \delta H)$. Y_m is Young's Modulus of the magnetostrictive material.

Task #4. Laminate structure investigation

Produce laminated structure. Dimension of the magnetic material and relaxor piezoelectric single crystals will be engineered to optimally couple magnetostrictive effects and piezoelectric effects. Interface and bonding of the different materials and electrode coating will be investigated.

Task #5. Characterization of the magnetic sensors

A variable magnetic field will be setup and the sensitivity of the magnetic sensor will be determined in various configurations.

Task #6. Final report

A final report will be submitted by Ferro Solutions at the completion of the phase I program.

Time Schedule

The entire Phase I program will be completed in [redacted]. Table 1 details the schedule for each main task described in the above subsection.

Table 1. Project Time Schedule

Tasks	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
1. g_{33} mode sensor prototype	x	x				
2. Magnetic materials selection and optimization	x	x	x	x		
3. Piezoelectric materials selection and optimization	x	x	x	x		
4. Laminate structure investigation			x	x	x	x
5. Characterization of this magnetic sensors					x	x
6. Final report						x

5. 1. Phase I Option

During the transition period between Phase I and Phase II, FerroSolutions will further optimize the novel PME33 magnetic sensor including materials and fabrication process based on our Phase I results. All the issues involved in improvement of the device performance will be extensively analyzed. An improved sensor design, fabrication and characterization will be performed.

References

1. Yi-Qun Li, and Robert O'Handley, J. Appl. Sensing technology, 17, 10(2000).
2. B.J. Lynch and H.R.Gallantree, GEC Journal of Research, Vol. 8, No.1, 1990.
3. James E. Lenz, Proceedings of the IEEE, 78, 973(1990).
4. M. D. Mermelsten, IEEE Trans. On Magn., Vol. 28, No. 1, January (1992).
5. J. L. Preto, etc. IEEE Trans. On Magn., vol. 34, No.6, November (1998).
6. Seung-Eek Park and Thomas R. Shrout, J. Appl. Phys. 82 (4), 15 August (1997).
7. R.C. O'Handley, "Magnetic materials for sensors", proceedings of the ASTM Conference, Chicago, November 4, 1992.
8. Richard L. Copeland, Markus Kopp and R.C. O'Handley, "Analysis of magnetoelastic sensor", IEEE Trans. On Magn., Vol. 30, No. 5, September(1994).
9. R.C.O'Handley, "New spin-valve magnetic field sensors combined with strain sensing and strain compensation", IEEE Trans. On Magn., Vol. 31, No. 4, July(1995).

6. Related Work

The P.I. has made and characterized a variety of magnetic field sensors including prototype magnetostrictive/PZT passive field sensors.

The CTO of Ferro Solutions has extensive experience with magnetic materials in general and in particular has invented and published extensively on magnetic sensors and devices[1,7,8,9].

Ferro Solutions will work closely with Prof. Yet-Ming Chiang, consultant for this program, in relaxor piezoelectric single crystals optimization and evaluation.

7. Relationship with Future Research or Research and Development

The goal of this program is to provide the DoD and the commercial market with a new type of low-cost, low-energy-consumption and high-sensitivity magnetic sensor. The anticipated results from the proposed phase I program will provide critical information on optimization and fabrication of the magnetic sensor during the phase II effort. Ferro Solutions is committed to the commercialization of successful product concepts which emerge from government sponsored programs. The device design and fabrication knowledge generated over the contract period will be crucial for the commercial device development and manufacturing.

8. Commercialization Strategy

Ferro Solutions is a recent start-up company with the mission of developing and manufacturing novel materials-based device products, specifically ferromagnetic and ferroelectric's materials based devices.

A very large market is anticipated for the low-cost, low-energy-consumption, high-sensitivity passive relaxor piezoelectric magnetic field sensors. It is expected that this sensor will replace many of the expensive and delicate instrument such as optically pumped magnetometer and SQUID for applications in magnetic detection and classification of ships, sea mines and unexploded ordnance for Navy, security for installations, perimeters, and borders, monitor urban or highway traffic.

Our strategy to commercialize this technology is to develop and demonstrate our unique technology and then team up with other magnetic sensor manufacturers who are technology capable and have large volume manufacture and marketing capability. Thus, our technologies can effectively penetrate the magnetic sensor market.

Spinix Corp., a pioneer in novel magnetic sensor development and manufacturer will invest and team up with us in developing the magnetic sensors as soon as the phase I program completed and the feasibility of the concept is successfully demonstrated. Significant commercial investment is expected during Phase II period of this program.

9. Key Personnel

Mr. Jiankang Huang, Principal investigator
President, Ferro Solutions

Mr. Huang has more than ten years R&D experience in ferromagnetic materials, ferroelectric materials and related devices. He is the president of Ferro Solutions and a research affiliate at MIT. He has been in charge of magnetostrictive materials development in high-sensitivity magnetic sensors at NZAT Applied Technologies from 1998 to 2000. He successfully developed magnetostrictive thin films for two Phase II SBIR projects. After NZAT was acquired by Corning Corp. in 2000, he has been working in electro-optical ceramic materials and devices. Mr. Huang was a visiting scientist in Department of Material Science and Engineering at MIT from 1995 to 1998, where he and his colleagues discovered the magnetic-field-induced strain in the martensitic phase of single-crystal shape memory material Ni_2MnGa. This discovery leads to a new class of actuator materials: Ferromagnetic Shape memory Alloy (FSMA). Before coming to MIT, Mr. Huang worked in magnetic materials in Chinese Academy of Sciences in Beijing, China. He received his BS and MS in physics at Beijing University in 1985 and 1991 respectively.

Selected Publications:

- **Patent (pending)**
  "Dual-Tuning Microwave Devices Using Ferroelectric/Ferrite Layers", Hua Jiang, Wei Hu, Vladimir Fuflyigin, Shaohua Liang, Yi-Qun Li, and **Jiankang Huang.**
- **Journal Papers**
  1. "Field-induced strain under load in Ni-Mn-Ga magnetic shape memory materials", S.J.Murray, M. Farinelli, C. Kantner, **J.K.Huang**, S.M.Allen, and R.C.O'Handley, J.Appl Phys.,83, 7297(1998).

2. "Metalorganic Chemical Vapor Deposition of Magneto-Optical Ce:YIG Thin Films", Yi-Qun Li, Mondher Cherif, **Jiankang Huang**, Wayne Liu, and Qiushui Chen, Proceedings of the 1998 MRS Spring Symposium, 517, 449(1998).
3. "Magnetic-field-induced strains in Ni_2MnGa shape-memory alloy", K.Ullakko, **J.K.Huang**, C.Kantner, V.V.Kokorin and R.C.O'Handley, J. Appl. Phys. 81, 5416(1997).
4. "Magnetically controlled shape memory effect in Ni_2MnGa intermetallics", K. Ullakko, **Jiankang Huang**, V. V. Kokorin, and R. C. O'Handley, Scripta Materialia, 36 1133,(1997).
5. "Large magnetic-field-induced strains in Ni_2MnGa single crystals", K. Ullakko, **J. K. Huang**, C. Kantner, and R. C. O'Handley, and V. V. Kokorin, Appl. Phys. Lett. 69, 1966(1996).

Dr. Robert O'Handley, Senior Scientist
Chief Technology Officer, Ferro Solutions

R.C. O'Handley received his Ph.D. in Physics in 1972 from the Polytechnic Institute of Brooklyn (now the Polytechnic University) for magnetic resonance studies of gadolinium thin films. He was a National Research Council Postdoctoral Research Associate at Michelson Lab, China Lake, CA, where he used polarization modulated ellipsometry to study surfaces of silver films in ultrahigh vacuum.

In July, 1974 he joined Allied Chemical's Materials Research Center, Morristown, NJ, to start a group investigating the magnetic properties of amorphous metallic alloys. At Allied he contributed to the understanding of both the fundamental and technical properties of these novel materials. Particularly noteworthy are his pioneering studies of magnetoelastic phenomena and his successful development of high-induction metallic glasses for power transformer applications.

In Sept. 1978 he became a research staff member at IBM's Watson Research Center where he solved materials problems facing the development of multilayer composite chip carriers. Since coming to MIT in January 1981 he has expanded his research horizons to include synthesis and characterization of strongly magnetic icosahedral phases as well as pioneering processing and characterization of new high-energy-product Fe-Nd-B permanent magnets. He also contributes to the development of high T_C oxide superconductors and perpendicular magnetization via magnetoelastic coupling in epitaxial Cu/Ni/Si (001) films. Most recently, he has discovered and pursued the development of giant magnetic-field-induced strains in martensitic Heusler alloys based on the shape-memory material, Ni_2MnGa.

Dr. O'Handley has authored a widely used textbook, *Modern Magnetic Materials, Principles and Applications*, written several chapters for other books and published more than 200 scientific and technical papers on magnetic, electrical and other physical properties of solids. He is active in the IEEE Magnetics Society and in the annual Conference on Magnetism and Magnetic Materials, for which he has been a publications chairman, secretary and treasurer. He is a member of the scientific advisory board of the Chinese National Magnet Lab, Beijing, PRC, and is on the editorial board of Materials Letters.

He holds sixteen U.S. and international patents on magnetic materials and devices. His discoveries made possible the development of a new active materials company, AdaptaMat, as well as sensor manufacturers, Spinix and FerroSolutions (where he is the Chief Technology Officer). He has consulted for many industries including IBM, DEC/Quantum Corp., and Sensormatic.

Selected Publications

Relevant Books, Chapters and Review Papers

1. "*Modern Magnetic Materials: Principles and Applications*", R. C. O'Handley,(Wiley,1999).
2. "Hall Effect in Amorphous Metals", chapter in *The Hall Effect and Its Applications*, T.R. McGuire, R.J. Gambino and R.C. O'Handley, ed. C.-L.Chien and C.R. Westgate (Plenum, NY, 1980), p.137.
3. "Hall Effect Formulae and Units", R.C. O'Handley, chapter in *Hall Effect and Its Applications,* ed. C.-L. Chien and C.R. Westgate (Plenum Press, NY, 1980) p. 417.
4. "Fundamental Magnetic Properties", R.C. O'Handley, chapter in *Amorphous Metallic Alloys*, ed. F.E. Luborsky (Butterworths, London, 1983) p. 257.
5. "Physics of Ferromagnetic Amorphous Alloys", R.C. O'Handley, Invited review paper, J. Appl. Phys. **62**, R15 (1987).
6. "Magnetostriction and Magnetoelastic Effects", R.C.O'Handley, Chapter in *Modern Methods in Materials*, (John Wiley, N.Y., 1999).
7. "Magnetic Materials", R. C. O'Handley, entry in *Encyclopedia of Physical Science and Technology*, Third Edition, ed. R.A. Myers (Academic Press, 2001).

Other Sensor-related Publications

1. "An Innovative Passive Solid-State magnetic Sensor", Yi-Qun Li, and Robert O'Handley, J. Appl. Sensing technology, 17, 10(2000).
2. "Magnetostriction of Ferromagnetic Metallic Glasses", R.C. O'Handley, Sol. St. Comm. **21**, 1119 (1977).
3. "Temperature Dependence of Magnetostriction in $Fe_{80}B_{20}$ Glass", R.C. O'Handley, Sol. St. Comm. **22**, 485 (1977).
4. "Spontaneous Hall Effect and Resistivity of Fe-Co-Ni-B Glasses", R.C. O'Handley, Phys. Rev. **B 18**, 2577 (1978).
5. "Magnetostriction of $Fe_{100-x}B_x$ Glasses", R.C. O'Handley, M.C. Narasimhan and M.O. Sullivan, J. Appl. Phys. **50**, 1633 (1979).
6. "Elastic Constant Anomaly in $Fe_{80-x}Mo_xB_{20}$ Metallic Glasses",C.-P. Chou and R.C. O'Handley, J. Non-cryst. Sol. **40**, 417 (1980), and in *Electrical, Magnetic and Optical Properties of Glasses*", ed. M. Tomozawa et al., (North Holland, NY, 1980) p. 417.
7. "Magnetostriction in $Co_{80-x}T_xB_{20}$ (T = Fe, Mn, Cr, V) Glasses", R.C. O'Handley and M.O. Sullivan, J. Appl. Phys. **52**, 705 (1981).
8. "Opportunities in Magnetic Anisotropy and Magnetostriction", R.C. O'Handley, Mat Sci. and Eng. **B 3**, 365 (1989).
9. "Magnetic Materials for EAS Sensors", R.C. O'Handley, J. Mtls. Engineering and Performance **2**, 211 (1993).
10. "Analysis of a Magnetoelastic Sensor", R.L. Copeland, M. Kopp, and R.C. O'Handley, IEEE Trans. Magnetics **MAG-30**, 3399 (1994).
11. "New Spin Valve magnetic field sensor combined with strain sensing and strain compensation", R.C. O'Handley and J.R. Childress, IEEE Trans. **MAG-31**, 2450(1995).
12. "Development of a Pinned Wall Sensor Using Cobalt-rich, Near-zero Magnetostrictive Amorphous Alloys", C.K. Kim and R.C. O'Handley, Metal. and Mater. Trans. **28A**, 423 (1997).
13. "6% magnetic-field-induced strain by twin-boundary motion in ferromagnetic Ni-Mn-Ga", S.J. Murray, M. Marioni, S.M. Allen, R.C. O'Handley and T.A. Lograsso, Appl. Phys. Lett. **87**, 886 (2000).
14. "AC performance and modeling of ferromagnetic shape memory actuators", Christopher P. Henry, Jorge Feuchtwanger, David Bono, Miguel Marioni, Pablo G. Tello, Marc Richard, Samuel M. Allen, and Robert C. O'Handley, Proc. SPIE **4333**., **151** (2001).

10. Facilities/Equipment

Ferro Solutions has full access to Dr. Robert O'Handley's Lab at MIT for research and development. Manufacturing facilities will be built up in Ferro Solutions to produce commercial products.

The major facilities and equipments in Dr. Robert O'Handley's Lab include the followings:

Vibrating Sample Magnetometers (VSM), torque magnetometer, inductance and impedance bridges, spectrum analysis and other electronic for low-field magnetic and magnetostrictive measurement.

A broad range of processing and characterization equipment, relevant to development of piezoelectric materials, is available in Prof. Yet-Ming Chiang's Lab, including the following. 1) A laboratory for inorganic materials synthesis including wet chemical equipment, glove boxes, freeze-driers, calcining and sintering furnaces, hot-pressing facilities. 2) Dielectric, electrical, electromechanical, and thermomechanical testing facilities. 3) Materials characterization facilities including environmental SEM, high resolution SEM, TEM, STEM, AFM, and surface analytical equipment.

11. Consultants

Yet-Ming Chiang, Kyocera Professor of Ceramics, MIT.
Project Responsibilities: supply, optimize and evaluate relaxor piezoelectric single crystals.

Professional Employment, Other Positions Held, and Affiliations:
Professor, Department of Materials Science and Engineering, MIT, July 1994 - present
Visiting Research Scientist, DuPont Central Research, Wilmington, Delaware, Jan.-Dec. 1992
Associate Professor, MIT, July 1988 - June 1994
Assistant Professor, MIT, January 1985 - June 1988
Editorial Boards of *Current Opinion in Materials Science and Engineering, Journal of the American Ceramic Society, Journal of Electroceramics*
Materials Consultant, *The Oklahoma City National Memorial Foundation*, April 1998-August 1999

Honors:
Ross Coffin Purdy Award, (with H.D. Ackler, for best paper in the *Journal of the American Ceramic Society* in 1999), The American Ceramic Society, April 2001
R.M. Fulrath Award, The American Ceramic Society, 2000
F.H. Norton Award (Outstanding New England Ceramist), The American Ceramic Society, 1999
Fellow, The American Ceramic Society, 1998
Kyocera Professorship, 1989-present
ONR Young Investigator Award, 1988-1991
Mitsui Career Development Award, 1987-1989
DuPont Faculty Development Award, 1985-1987
IBM Graduate Fellowship, 1982-1984

Selected Relevant Publications

- S.A. Sheets, A.N. Soukhojak, N. Ohashi and Y.-M. Chiang, "Relaxor Single Crystals in the $(Bi_{1/2}Na_{1/2})_{1-x}Ba_xZr_yTi_{1-y}O_3$ (BNBZT) System Exhibiting High Electrostrictive Strain," *J. Appl. Phys.*, **90**[10] 5287-5295 (2001).
- B.P. Nunes, J. Shen, A.N. Soukhojak and Y.-M. Chiang, "Shaped Growth of Oriented Single Crystal Rods and Fibersin the $(Bi_{1/2}Na_{1/2})_{1-x}Ba_xZr_yTi_{1-y}O_3$ (BNBZT) System," Proceedings of 10th US-Japan Seminar on Dielectric & Piezoelectric Ceramics, Newport, RI, Sept. 27-29, 2001.
- N. Ohashi, A. N. Soukhojak, G. W. Farrey, S. A. Sheets, and Y.-M. Chiang, "Liquid Phase Epitaxial Growth of Perovskite $(Bi,Na)TiO_3$ and Solid Solutions on $SrTiO_3$ (001) Substrates," *Proceedings of the 2000 12th IEEE International Symposium on Applications of Ferroelectrics*, IEEE Catalog Number 00CH37076 (ISBN 0-7803-5940-2), pp. 553-556 (2001).

- A.N. Soukhojak and Y.-M. Chiang, "Generalized Rheology of Active Materials," *J. Appl. Phys.*, **88**[11] 6902-6909 (2000).
- A.N. Soukhojak, H. Wang, G.W. Farrey, and Y.-M. Chiang, "Superlattice in Single Crystal Barium-Doped Sodium Bismuth Titanate," J. Phys. Chem. Solids, 61[2] 301-304 (2000).
- Y.-M. Chiang, G.W. Farrey, and A.N. Soukhojak, "Lead-Free High Strain Single Crystal Piezoelectrics," Appl. Phys. Lett., 73[25] 3683-3685 (1998).

Education

Sc.D. M. I. T., 1985.
S.B. M. I. T., 1980.

12. Prior, Current or Pending Support of Similar proposals or Awards.

No prior, current or pending support for the proposed work.

13. Cost Proposal

See next page.

PROPRIETARY
U.S. DEPARTMENT OF DEFENCE
SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM

COST PROPOSAL

1. Name of offeror: Ferro Solutions
2. Home office address: 204 Norfolk Street, Cambridge, MA 02139
3. Location where work will be performed: 77 Mass Ave. Cambridge, MA 02139
4. Title of proposed effort: A Passive Relaxor Piezoelectric Magnetic Sensor
6. Topic number and title: N02-066
7. Total dollar amount of proposal: **$ 99,895** **Base** **69,914** **Option** **29,981**

5. Taxpayer ID #*:
5.CAGE Code*:

8. Direct Materials Costs			Proposal		Option	
Type	Unit Cost	Unit	Qty	$	Qty	$
PZT-5 compressional crystals	650.00	lot	1	650		
Relaxor Single Crystal	1,050.00	ea	2	2,100		
FeCo Alloy						
Ni Alloy						
Metal Glass						
	Total Material Costs			2,750		0
rials Overhead	None					
10. Direct Labor						
Type		Hourly Rate	Hours	$	Hours	$
Principal Investigator	HUANG, Jiankang		425	17,000	225	9,000
Senior Scientist	O'HANDLEY, Robert		80	4,000	70	3,500
11. Total Direct Labor & Overhead			505	35,700	295	21,250
12. Equipment Usage						
Type		Rate/hr	Hours	$	Hours	$
Lab usage		10	600	6,000	210	2,100
	Total Equipment Usage Cost			6,000		
13. Special Equipment				0		
14. Travel (conference)				0		
15. Subcontracts				0		
15 A. Outside Service (Piezoelectric)	**Chiang, Yet-Ming**			10,000		
16. Other direct costs						
	Sub – Total (7 - 15)			54,450		23,350
17. G&A Expense	All Cost above this line			10,890		4,670
18. Royalties			0.0%	0		0
19. Fee or Profit	All Cost above this line		7.0%	4,574		1,961
20. Total Cost and Fee or profit				69,914		29,981

21. Signed by ____________________ [redacted] Name and Title: Jiankang Huang President

22.a Has any executive agency of the United States Government performed any review of your accounts or records in connection with any other government prime contract or subcontract within the past twelve months? No

b. Will you require the use of any government property in the performance of this proposal? No

c. Do you require government contract financing to perform this proposed contract? Yes, Prograss Payments

23. Type of contract proposed: Fixed price

* FerroSolutions is not yet incorporated at this moment. Taxpayer ID and CAGE Code will be available before award.

EXHIBIT C

From: "Douglas Harry, ONR SBIR Program Manager" <harryd@onr.navy.mil>
To: "jiankang.huang@att.net" <jiankang.huang@att.net>
Cc: "jiankang.huang@att.net" <jiankang.huang@att.net>
Subject: ONR 364 SUPPORT FOR PHASE I PROPOSALS UNDER THE DOD SBIR PROGRAM SOLICITATION [redacted]
Date: Thu, [redacted] 10:47:30 -0400

Congratulations, your Small Business Innovation Research (SBIR) Program [redacted] proposal under topic number [redacted], entitled "A Novel Vibration Energy Scavenging (VES) System ", was one of eighty-nine (89) selected for support by the Office of Naval Research, ONR 364 (see "What's New" at the Navy SBIR Home Page, http://www.onr.navy.mil/sbir). If you haven't received the associated Purchase Order for Work or Services (PO), it should be issued by our Acquisition Department (or that of the Naval Air Systems Command) soon to authorize the proposed work to begin on or before [redacted] (some awards began as early as [redacted]. Please note that no proposed work or purchases are authorized until a PO is issued. The contract number, cognizant Science and Technology Program Officer (S&T PO) or Technical Point of Contact (TPOC), and the schedule for deliverables will be specified in the PO. In order to receive prompt payments for your deliverables and to propose timely follow-on contracts for further research & development (Phase II), I encourage you to review and follow the guidelines for the ONR SBIR Program which are provided below, in the attachment, &/or at the specified websites.

If you are not registered in the DoD Central Contractor Registry and have not provided your IRS identification number, CAGE Code and DUNS number, please register on-line at http://www.ccr.dlsc.dla.mil/, and provide this data as soon as possible to me, and I will assist you as I am able.

A Data/Report Requirement at our website, http://www.onr.navy.mil/sci_tech/industrial/sbir_onr.htm, will describe the specific deliverable (Services/Supplies Item) required for each payment listed in the PO; e.g., the [redacted]-month progress reports (i.e., Items 0001AA & 0001AB) -- please note that our Home Page will be updated later this month. Since the S&T PO's and/or TPOC's comments should be addressed in your final Technical Report (0001AD), I encourage you to submit a draft Technical Report & preliminary Phase II plan as yo of the 5th month. Also note that unlike requirements for most other R&D (cost reimbursable) contracts and grants, your final Technical Report will be due six (6) months after the effective start date (as early as [redacted]. Acknowledgements of the Navy SBIR Program will be greatly appreciated. In addition please note that since payments may not occur until 30-days after acceptance of each

deliverable, the first payments are the highest, even though they may be disproportionate to the actual time applied to that portion of the effort.

ONR S&T POs usually manage basic & applied research relevant to your proposal and work closely with their associates at the Naval Systems (Acquisitions) Commands, so their input with respect to possible support for follow-on R&D (Phases II & III) is important. It is my intention for the TPOCs assigned to certain Phase I awards to convey your p S&T PO's position back to you in a timely fashion. However please note that these individuals are only "one deep," and they travel frequently.

I will attempt to expedite solicitations of formal Phase II proposals and negotiations of those contract awards that will be jointly funded (i.e., partially supported by a non-SBIR government program and/or a private-sector source). It is hoped that most Phase II decisions will be made on the basis of your preliminary Phase II plans at the presentation of results during the sixth month. In [redacted] the balance of about forty (40) [redacted] topic Phase II proposals will be selected for contract awards to begin in [redacted] Note that exercise of the [redacted] bridge option is usually contingent on support for the [redacted] Phase II proposal, and that the Phase I option will expire on or about the end of the ninth month, if it was proposed and included in the PO.

I look forward to your progress in Phase I. Please forward a copy of your progress reports, technical reports, and Phase II plans to me via e-mail. If I receive them electronically, I do not want to receive a hard copy. Don't hesitate to contact me by phone: (703) 696-4286; FAX: (703) 696-4884; or E-mail: harryd@onr.navy.mil, as required.

Respectfully,

Doug Harry

Mailing address (for First Class Mail):
Office of Naval Research - Small Business Innovation Research (ONR SBIR Prgm Mgr)
ATTN: Mr. Douglas R. Harry, ONR 364
800 N. Quincy Street (B.C.T. #2, Room 106)
Arlington VA 22217-5660

Hand Carry Address (for Express Mail, FedEx, etc.):
801 N. Randolph Street (B.C.T. #2, Room 106)
Arlington VA 22203

Phone: (703) 696-4286 FAX: (703) 696-4884

Attachment 1: ii-planng attchmt.doc (application/msword)